

Accuracy and Precision of the NOAA Aeronomy Laboratory Pressure Temperature Instrument on the NASA WB-57F

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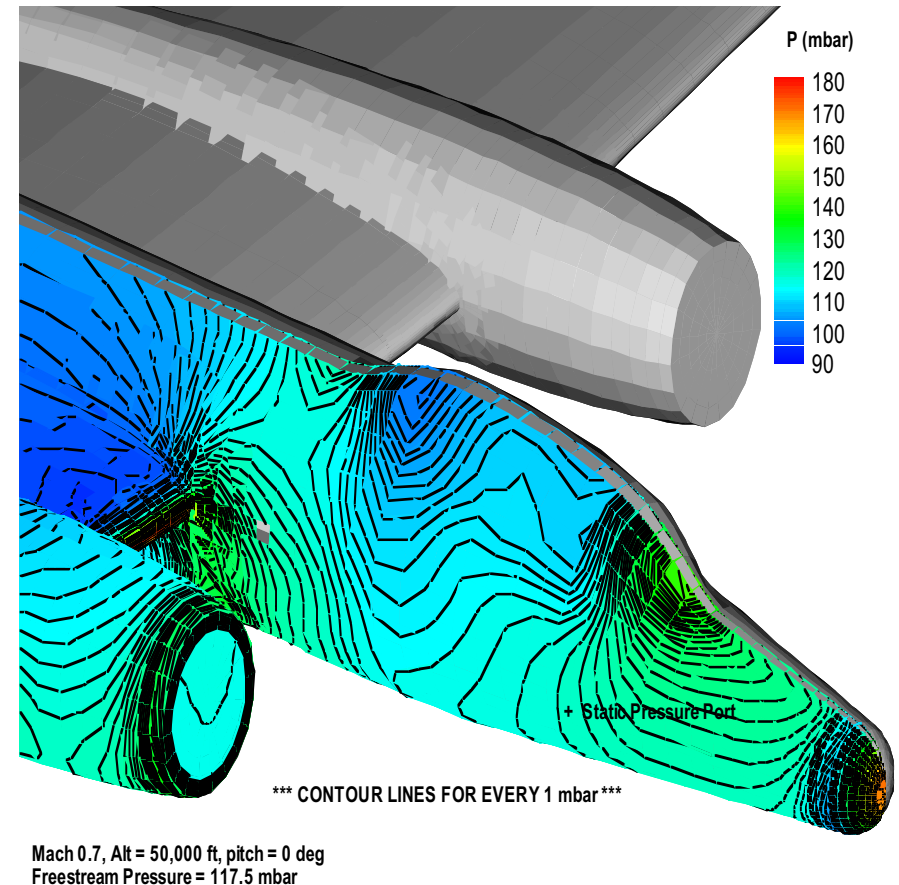
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Theory of Operation for the PT Probes on the WB-57F

Measuring temperature and pressure on an aircraft that is moving at speeds up to 0.7 times the speed of sound at pressures ranging from 500 to 50 mb is difficult. Not only do the pressure and temperature probes have to have good precision and accuracy, the aerodynamic design and placement of the probes is also critical. When a temperature probe is placed in the air stream at these high velocities, the temperature measured is not equivalent to the static air temperature, but includes the addition of thermal energy from the conversion of the kinetic energy of the flight. This warming has to be accounted for in order to determine the actual temperature of the atmosphere at the aircraft altitude. In order to do this, the warming effect on the probe, which is a function of its geometry, must be known as well as the ram pressure at the probe due to the aircraft velocity. Also, the actual pressure of the atmosphere at the aircraft altitude must be known. This pressure, which is referred to as the static pressure, is extremely difficult to measure accurately because the air moving across the aircraft surface creates pressure

enhancements and depletions that are a function of port position and aircraft attitude. The figure below shows results of a model run of showing pressure variation on the skin on the aircraft for specific flight conditions.



In order to make an accurate temperature and pressure measurement, a Weston digital pressure temperature transducer is used to measure both static and ram pressure. These transducers are accurate to within $\pm 0.01\%$ of full-scale or ± 0.1 mbar. When the aircraft was manufactured, two ports on either side of the aircraft were placed at positions where the air moving across the skin is perpendicular to the port. These ports are connected together and to the static pressure transducer. The ram pressure measurement consists of a forward-looking tube with a wide-angle opening connected to the ram pressure transducer. The ram pressure is calculated by subtracting the static pressure from this measurement.

The temperature probes consist of a slow and fast responding type 102 probe from Goodyear Aerospace Corporation. The platinum wire temperature sensor in the type 102 probe is calibrated to less than ± 0.1 degree.

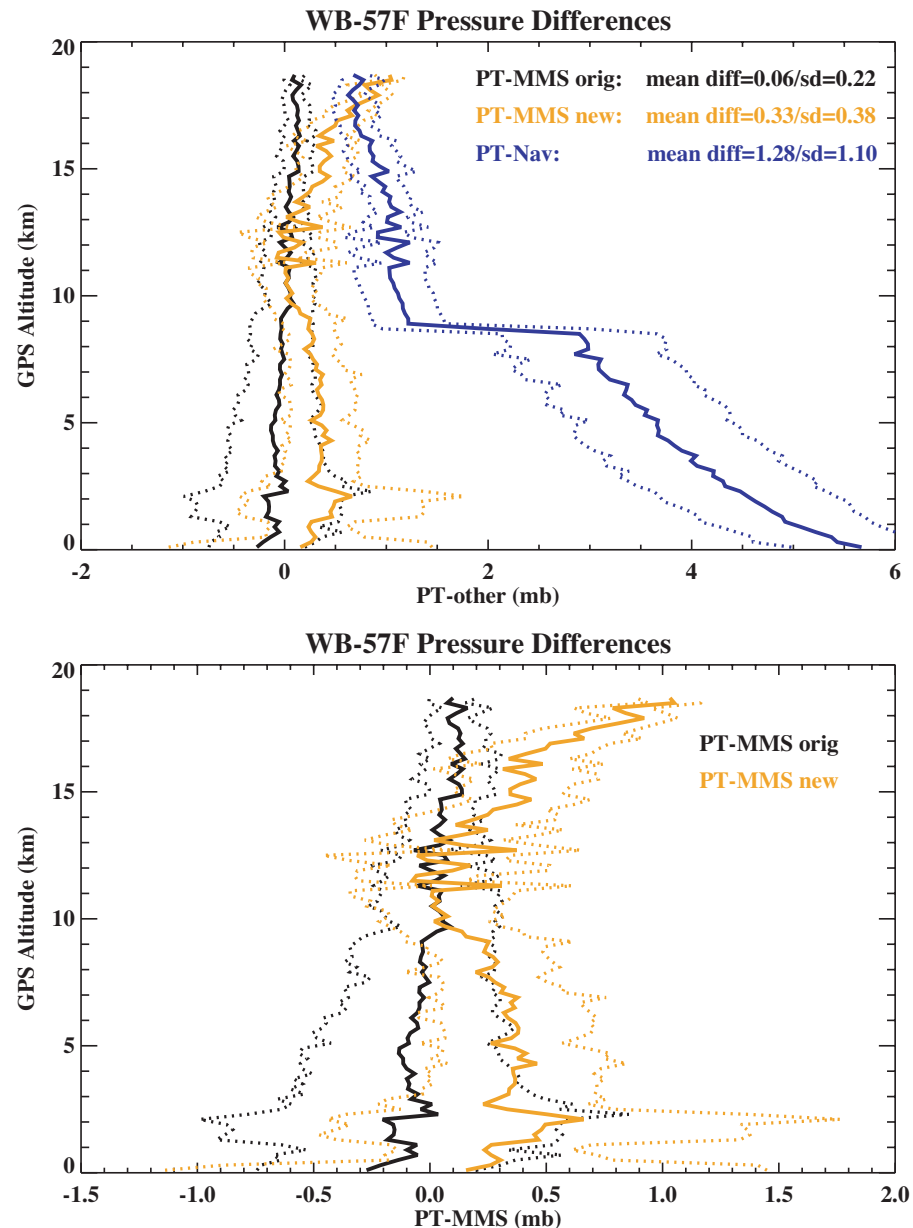
Data is gathered once every second from these probes using a custom data system. The Weston

pressure transducers are held at a constant temperature of 50 degrees Celsius in order to reduce temperature effects on the measurement and in order to prevent condensation within the sensor. The analog to digital converters are also held at a relatively constant temperature, and a thousand samples from each channel is averaged each second. This over sampling results in a precision of 0.03 degrees in temperature and 0.03 mbars in pressure. We estimate the total accuracy of these measurements in flight to be ± 0.5 degrees for temperature and ± 0.5 mb for pressure.

Static Pressure Differences

There were three pressure measurements recorded on the CRYSTAL-FACE WB-57F flights. These included those of the NOAA PT instrument, the NASA MMS instrument, and the aircraft navigational recorder system. The MMS and PT instruments measure off the same static line. Differences between the original MMS data and the PT data are then primarily a consequence of time lags in recording or actual pressure sensor measurement differences. MMS static pressure has since been revised adjusting according to information gained from the MMS calibration maneuvers. Differences between the new MMS pressures and PT pressures are now largely a function of that adjustment.

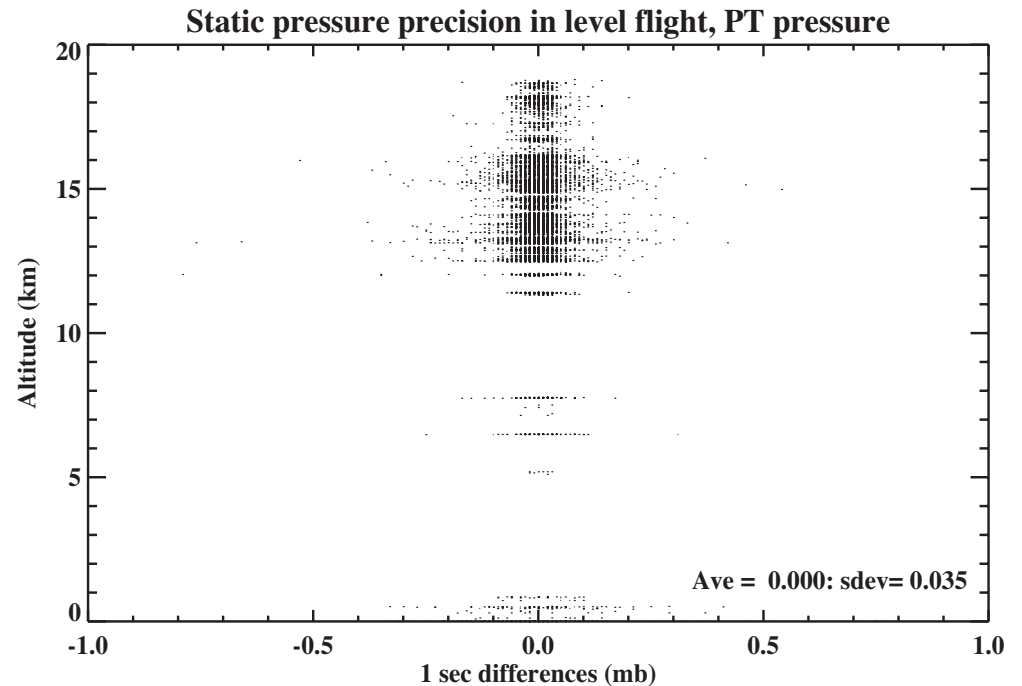
Differences are shown in the figure to the right. The mean difference in the raw MMS and PT pressures is 0.06 mb (sd=0.22). The revised MMS/PT difference is 0.33 mb (sd=0.38). The PT/Nav system differences are much larger, mainly reflecting the inaccurate pressure sensor used at pressure higher than 400 mb in the Nav recorder system.



Static Pressure Precision in Flight

The precision of the Weston digital pressure transducer on the ground is 0.03 mb. This has been confirmed by running the transducer on the ground for extended periods of time. Second to second variations in flight will be a function of the instrument precision and geophysical variations and the way the plane is flown. However, we have tried to estimate a precision of the instrument in flight by examining 1-second differences when the plane is flying level. The condition for level flight is that the change in GPS altitude is less than 0.2 m/sec, which encompasses 18% of all the CRYSTAL-FACE data. The results of this analysis are shown in the figure to the right.

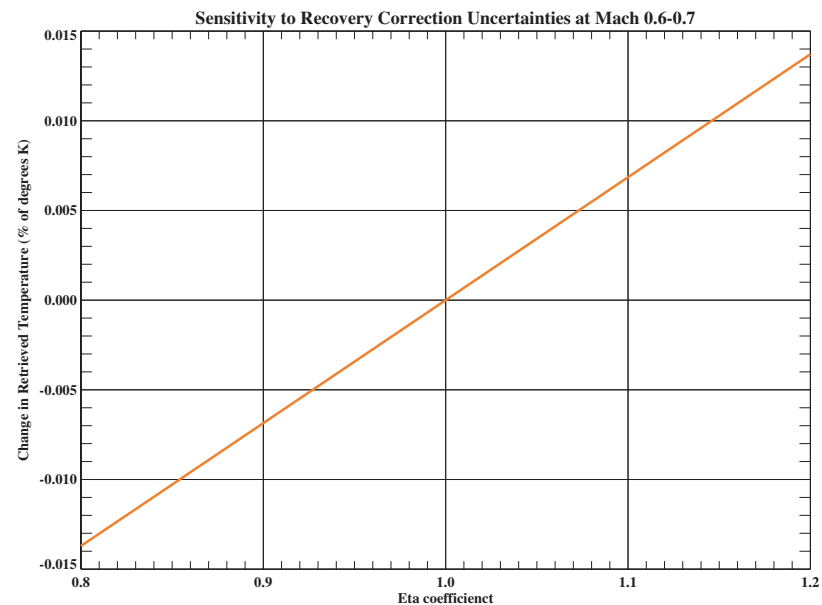
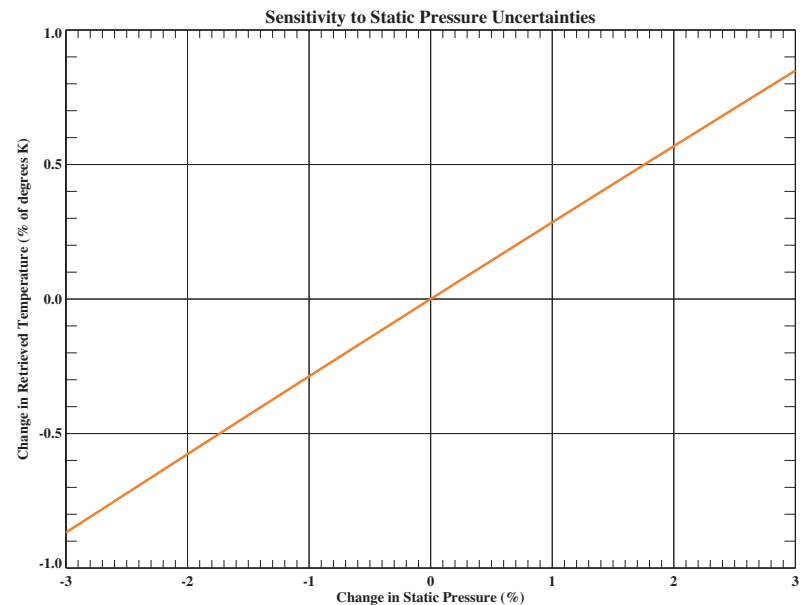
A conservative estimate of the in-flight precision is a doubling of the standard deviation. This gives a value of 0.07 mb.



Sensitivity to Parameters in the Temperature Retrieval.

The retrieved temperature is a function of the raw resistance measured by the probe, the calibration of the platinum wire temperature sensor, the calibration of the recovery factor, and the measured static and ram pressures. (For details, see Rosemount Technical Report 5755.) Results of a sensitivity study on static pressure and recovery factor are shown to the right.

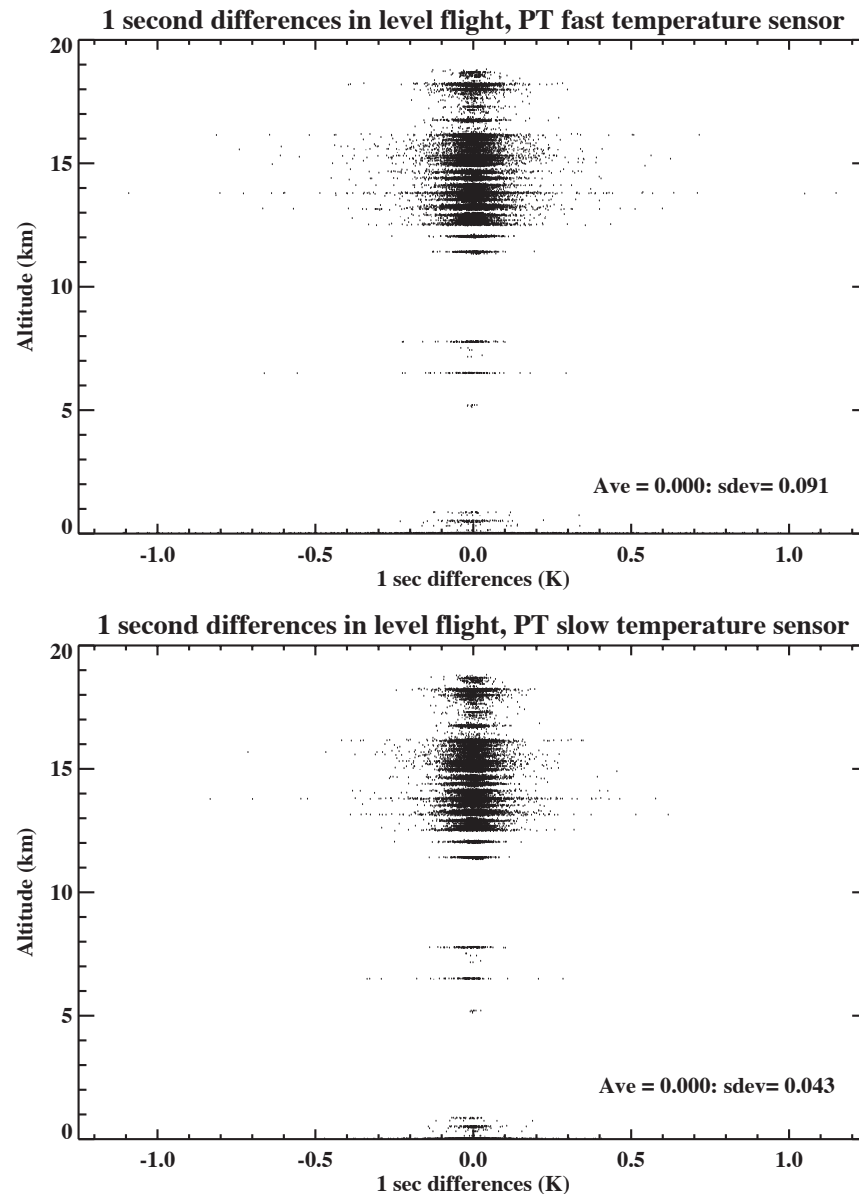
Changing the recovery factor over the 20% range shown in the Rosemount Technical Report 5755 changes the retrieved temperatures by less than 0.015%. Uncertainties in static pressure (and also in ram pressure) have a much larger effect. A 3% error in static pressure will result in a temperature error of $\sim 0.7\%$. During CRYSTAL-FACE, average 100 mb temperatures were ~ 205 K. A 3% error in static pressure would then translate into a temperature error of ~ 1.5 K (assuming no error in ram pressure).



Static Temperature Precision in Flight

The precision of the temperature sensors used in the PT instrument (both the 1 second and 5 second response sensors) is 0.03 K. This has been confirmed by making measurements in the laboratory for extended periods of time. As with the pressure transducer, 1-second variations in flight will be a function of the instrument precision and geophysical variations and the way the plane is flown. However, we have tried to estimate a precision of the instrument in flight by examining 1-second differences when the plane is flying level. The condition for level flight is that the change in GPS altitude is less than 0.2 m/sec, which encompasses 18% of all the CRYSTAL-FACE data. The results of this analysis are shown in the figure to the right.

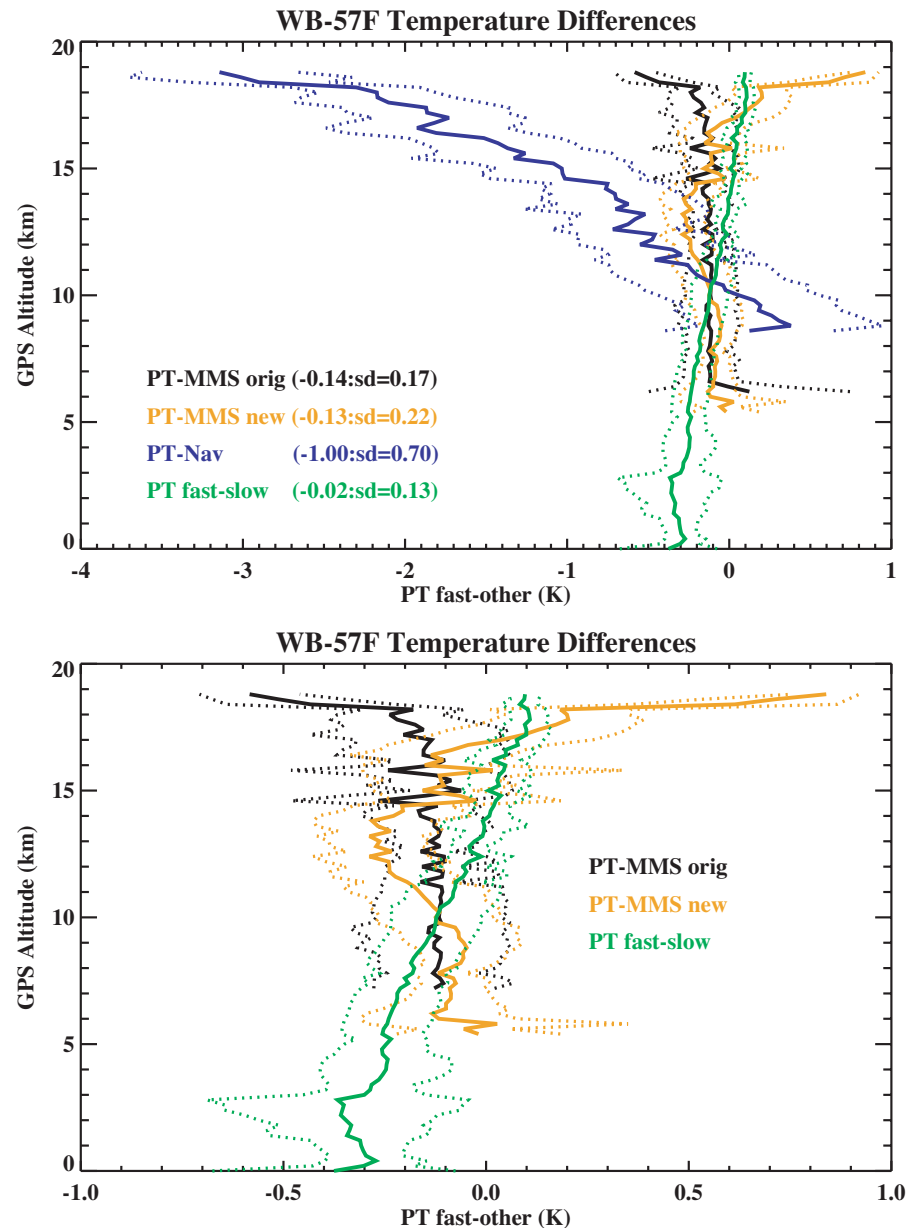
A conservative estimate of the in-flight precision is a doubling of the standard deviation. This gives a value of ~ 0.2 K for the 1 second sensor and ~ 0.1 K for the 5 second sensor.



Static Temperature Differences

There were four static temperature measurements reported on the CRYSTAL-FACE WB-57F flights. These included 2 from the NOAA PT instrument, one from the NASA MMS instrument, and one from the aircraft navigational recorder system. The MMS temperatures have been revised recently, however, we show comparisons here both with the originally submitted and newly revised MMS data. Differences are shown relative to the PT fast (1 second response) sensor. The average difference between the two PT sensors is -0.2 K with a standard deviation of 0.13K. There is an altitude dependence to the difference, this is more pronounced in aircraft during descent than in ascent.

The temperature comparison results are shown in the figure to the right. The mean differences between the MMS and the PT temperatures are less than 0.15 K for both the old and the new MMS data. The Nav system differences are much larger; this may partly be due to the fact that the Nav retrieval uses a retrieval that ignores the mach dependence in the recovery factor.



Sonde Temperature Comparison

In addition to comparing with coincident aircraft measurements, temperatures can also be compared with sondes. The stations used were:

Cape Canaveral, KXMR, 28.47N, 81.55W

Key West, KEYW, 24.55N, 81.75W

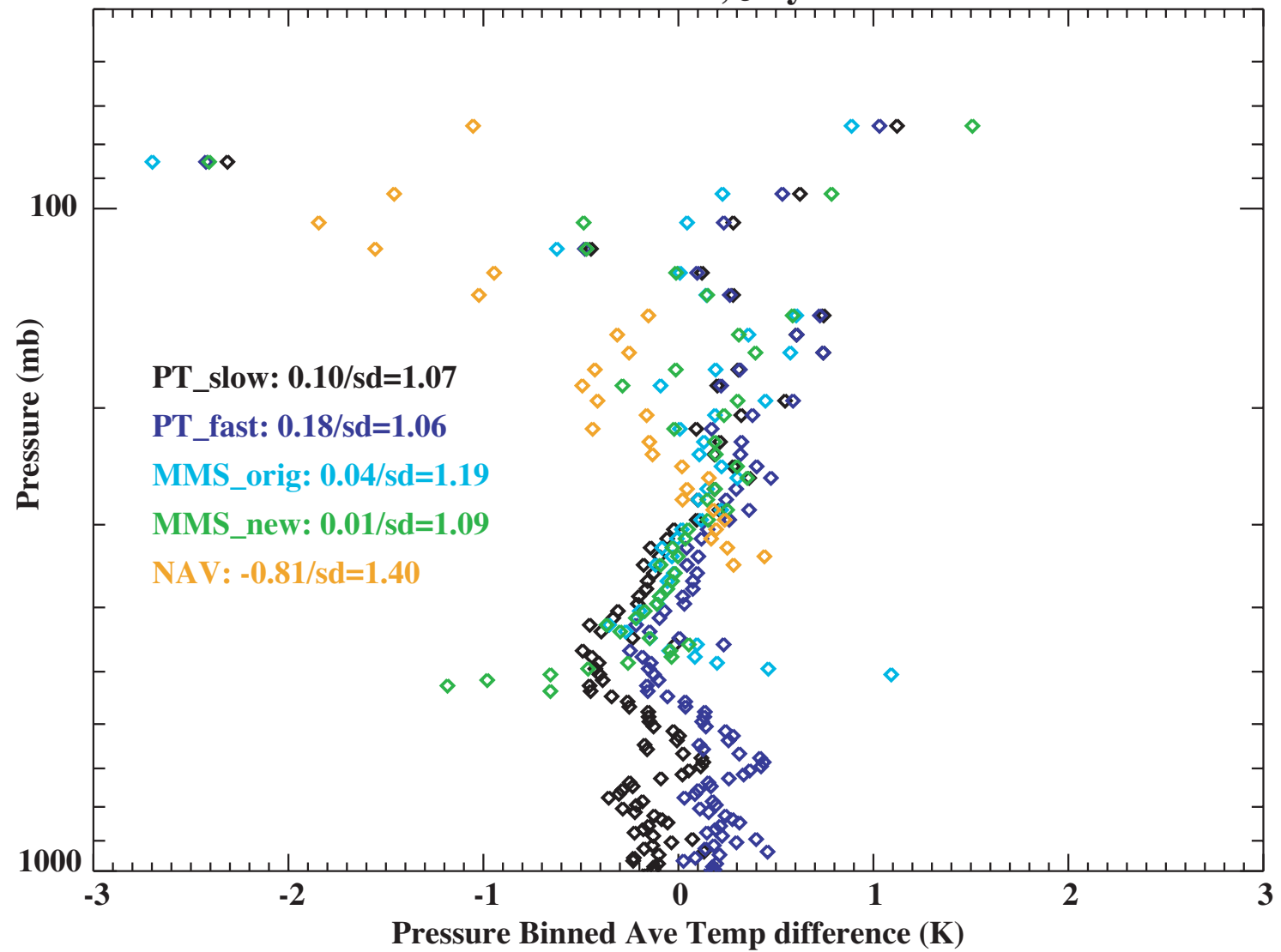
Miami, KMIA, 25.82N, 80.28W

Tampa Bay, KTBW, 27.7N, 82.4W

Nassau, Bahamas, MYNN 25.05 N, 77.47W

Coincidence criteria of 0.75 degrees in latitude and longitude and 5 hours in time were used. Sondes report temperature, pressure and geopotential height. The aircraft reports temperature, pressure and geometric height. To do this comparison, pressure was used as the common axis between aircraft and radiosonde measurements. (note, Vaisala sondes have a stated pressure accuracy of 0.5 mb and a temperature accuracy of 0.2 K) The sonde measurements were interpolated to the aircraft pressure, and the differences and standard deviations were computed based on the 1-hz aircraft measurements. Plotted below are 5 mb binned differences. The PT average is 0.1-0.2 K colder than the sondes, with the revised MMS 0.01 K colder. The standard deviations of the differences are on the order of 1 K.

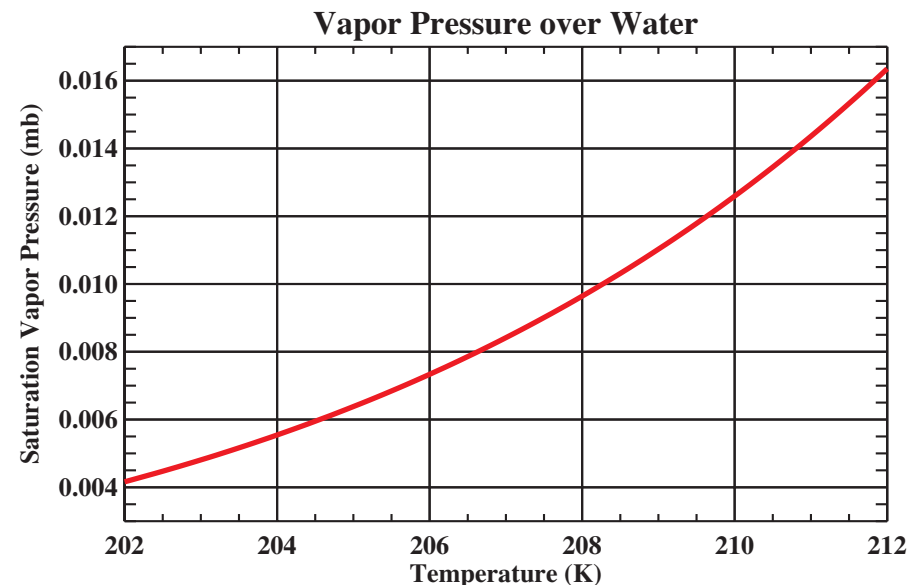
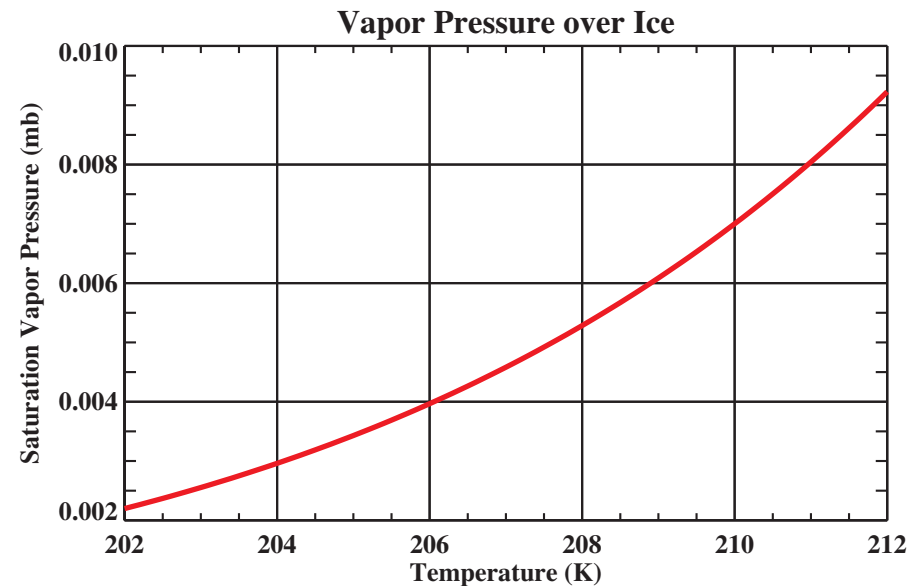
Sonde - WB57F, July 2002



Temperature Errors and Saturation Calculation

One question that needs to be addressed is "How accurate do the temperature measurements need to be?" One way the *in situ* aircraft temperature measurements are used is to compute the degree of water saturation. The saturation vapor pressure over ice is highly sensitive to temperature. The figures to the right show the sensitivity of the saturation vapor pressure to temperature over a range of cold temperatures that the WB-57F encounters regularly at static pressures in the vicinity of 100 mb.

The mean of the vapor pressures reported by the JLH instrument for the pressure range 95-105 mb is ~ 0.0006 mb. ~ 209 K gives 100% saturation with respect to ice for that water measurement. If the actual temperature is 209 K, but we report 210 K, the reported relative humidity will be $\sim 85\%$. If the reported temperature is 208 K, the reported relative humidity will be $\sim 115\%$, or a 15% RH error for a 1 K temperature error.



Summary

Prior to the CRYSTAL-FACE experiment, we estimated the accuracy of the PT temperature measurement to be 0.5K and the precision to be 0.1K. Comparisons with the MMS temperature measurements and radiosondes support these as conservative estimates.

Our prior estimate of the pressure measurement accuracy was 0.5 mb with a precision of 0.03 mb. The comparisons with MMS show agreement to within the accuracy stated. Our new estimate for in-flight precision is 0.07 mb.

To improve these measurements, we suggest a balloon aircraft comparison experiment. This would consist of flying a balloon instrumented with the same pressure transducer used on the aircraft, an accurate temperature sensor, and a GPS measurement. Including a GPS measurement on the balloon would allow a better assessment of the aircraft static port measurement.